UPWELLING AND MIXED LAYER DYNAMICS IN THE ARABIAN SEA

Mark E. Luther
Department of Marine Science
University of South Florida
140 Seventh Avenue South
St. Petersburg, FL 33701
Telephone: (813)553-1528 Fax: (813)553-1189 E-mail: luther@marine.usf.edu
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LONG-TERM GOALS

The ultimate goal of this research is to better understand the physics of the Indian Ocean circulation, the role of mixed layer physical processes in this circulation, and the role the Indian Ocean in global climate through the application and analysis of improved numerical models.

OBJECTIVES

The primary objective of this research is to implement and test improved mixed layer parameterizations in a layered numerical model of the Indian Ocean circulation. The improved mixed layer model is tested against available observations, against a previous version of the model that does not include explicit mixed layer physics and against similar models with different mixed layer parameterizations being developed at NRL-SSC by J. Kindle and collaborators. Improved mixed layer physics allow inclusion of thermodynamic forcing as well as wind stress forcing of the model circulation in order to understand the variability and complicated mixed layer physics observed in the Indian Ocean and to develop an optimum formulation for mixed layer physics in layered ocean models. Although these efforts are focused on the Indian Ocean, the formulation developed here can be extended to other areas of the world ocean. The extremes in atmospheric forcing found in the Arabian Sea provide the most difficult test of model mixed layer physics. The model provides a framework for interpreting the observations of mixed layer and coupled physical/biogeochemical processes from the ONR/JGOFS Arabian Sea Process Study and for basin-scale hydrographic observations made by WOCE in the Indian Ocean.

APPROACH

The ocean circulation model is based on the model of Luther and O'Brien (1985) as extended by Jensen (1991) and by J. Capella (personal communication). The present version of the model has 4 layers, with the horizontal pressure gradient assumed to vanish in the lowest layer (the reduced gravity approximation). The model domain covers the Indian Ocean basin from 30°S to 26°N and from 35°E to 120°E at a resolution of 1/12 degree in latitude and longitude. Thermodynamic forcing through a modified Kraus-Turner mixed layer parameterization as in McCreary et al. (1993) has been added to this version of the model by Zaihua Ji. Entrainment and detrainment processes are included that allow water to move between layers. Detrainment simulates the subduction of surface-layer water into the deeper ocean. The entrainment and detrainment processes are dynamically similar to the vertical mixing of momentum and heat that is present in continuously stratified models. The model is forced by observed fields of wind stress, wind speed, air temperature and humidity, with surface fluxes computed via bulk formulae from these and model sea surface temperature. J. McCreary of Nova Southeastern University has assisted in development and implementation of the mixed layer formulation and provided monthly mean climatological forcing fields. J. O'Brien and D. Legler at Florida State University provided interannual monthly mean atmospheric forcing fields.

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WORK COMPLETED

A near-real-time model integration continues using the non-thermodynamic (wind stress forcing only, no active mixed layer) version of the model with the monthly mean real-time winds processed at Florida State University. This integration has been completed for the period January 1977 through September 1997 and is updated through the 16th of the most recently completed month by the 5th working day of the present month to provide a near-real-time "quick-look" estimate of conditions in the Indian Ocean. The results from this model integration are available to the research community via anonymous ftp and the World Wide Web from ompl.marine.usf.edu. Output from the model has been provided to several ONR and JGOFS researchers participating in the Arabian Sea Process Study. The real-time data were provided to scientists aboard the RV Thomas G. Thompson on a workstation specially configured for the display of these data and of real-time satellite images prepared at the University of Miami via a satellite telecommunications link throughout the field phase of the Arabian Sea Process Study.

A 50-year integration of the thermodynamic (active mixed layer physics) model has been run using climatological monthly mean atmospheric fields from Rao et al. (1989) as forcing. A detailed analysis of the heat budget for the last year of this model integration has been completed (Ji and Luther, 1997). Numerous Lagrangian particle trajectory experiments have been run to study the pathways by which the heat balance is maintained (Haines et al., 1997a, 1997b). An interannual integration of the model has been completed for 1960 to 1989 using the atmospheric fields analyzed by Jones et al. (1995). This integration is being updated to the present time. An EOF analysis of this integration has been performed to quantify the interannual variability captured in the model fields.

As an expansion of this grant, we have established an online weekly electronic newsletter for the marine and aquatic sciences on the World Wide Web called HydroWire. HydroWire was conceived by representatives of AGU-Ocean Sciences, the American Society for Limnology and Oceanography, The Oceanography Society, and the Estuarine Research Federation. HydroWire was developed in our lab in collaboration with David Brooks at Texas A&M University and Omnet, Inc. The URL is http://www.hydrowire.org. To learn more about HydroWire, visit the home page and click on "About HydroWire."

RESULTS

An analysis of the FSU wind stress product shows that while wind stress was near its climatological mean during the southwest monsoon of 1995, wind stress curl was as much as 50% weaker than the climatological mean in the region of the Arabian Sea Process Study. Results from the non-thermodynamic version of the model driven by these winds show a deeper thermocline in this region due to reduced Ekman pumping. Comparison of the FSU winds with other wind products by J. Kindle at NRL show similar results in the FNOC and NCEP winds but not in the ECMWF winds. This implies that conclusions regarding the relative importance of Ekman pumping in mixed layer dynamics, particularly in nutrient injection into the photic zone, from the 1995 field observations are not representative of long-term climatological conditions during the southwest monsoon.

The heat balance of the Arabian Sea region in the thermodynamic model is maintained by a relatively shallow, rapid overturning circulation as seen by McCreary et al. (1993). Heat is transported northward across the equator in the thermocline layer in the western boundary region, entrained into the mixed layer in the northwestern Arabian Sea, with an equal amount of heat transfered to the mixed layer by surface fluxes. The heat budget is closed by an export of heat in the upper layer eastward across 80°E to the Bay of Bengal and then southward across the equator in the eastern tropical Indian Ocean.

Interplay between Ekman pumping dynamics lifting the thermocline and entrainment of thermocline water via mixed layer dynamics in the Arabian Sea plays an important role in the heat balance. Interannual variability in heat export from the Arabian Sea and in heat content of the eastern tropical basin may have significant impact for climate variability.

IMPACT/APPLICATIONS

The model provides a consistent framework in which to interpret and analyze the diverse observations taken during the Arabian Sea Process Study and the WOCE Indian Ocean Expidition. The model helps to quantify the role of mixed layer processes in the heat balance of the Indian Ocean and indentifies pathways by which this balance is maintained. The relative effects of wind stirring, convective overturning, Ekman pumping, and lateral advection in mixed layer evolution can be quantified in the model.

TRANSITIONS

We are exchanging model output and model forcing fields with J. Kindle at NRL. Output from these model integrations has been provided to R. Evans, A. Mariano, and D. Wilson-Diaz at the University of Miami for analysis in conjunction with the Patfinder SST data set. C. Flagg and H-S. Kim at Brookhaven National Lab are utilizing model fields and our EOF code in the analysis of the shipboard ADCP data from the Arabian Sea Process Study. We have provided model output for the location of the Arabian Sea moorings to R. Weller at WHOI for comparison with the mooring data. Subsets of model output are available on the WWWeb and via anonymous ftp to anyone interested.

As the model runs in an operational, near-real-time mode, it could easily be transitioned to operational Navy use.

RELATED PROJECTS

Under separate funding from NSF and NASA, a biogeochemical model has been coupled to the physical model. The improved mixed-layer formulation in the physical model provides information on mixed layer depth, nutrient entrainment and mixing intensity required by the biogeochemical model. The coupled physical-biogeochemical model will be applied to analysis and interpretation of the observations from the ONR-JGOFS Arabian Sea Process Study. In addition, the FSU surface meteorological fields and heat fluxes (Jones et al., 1995) have been correlated to CZCS chlorophyll pigment in the Arabian Sea to understand the relative roles of Ekman pumping, wind stirring, and convective overturning in driving primary productivity (Banse et al. 1997; Bartolacci and Luther, 1997).

Under funding from NSF, the thermodynamic model is being used to conduct tracer experiments to explain the distribution of Freons in the Indian Ocean (Haines et al. 1997a, 1997b). The tracer experiments are being used in the interpretation of the WOCE Hydrographic Program measurents made across the basin.

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http://ompl.marine.usf.edu

Contains images and output from the Indian Ocean models as well as information on Tampa Bay and West Florida Shelf projects, with links to HydroWire and other oceanographic sites.

ftp://kelvin.marine.usf.edu

cd pub/ndn: Anonymous ftp server containing gif images and data fields from Indian Ocean model integrations.